Design and Development of a 3 to 10 kW Ammonia Arcjet

K. D. Goodfellow*and J. E. Polk*
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

Abstract

An ammonia arcjet capable of throttling between 3 to 10 kW and producing a specific impulse of 600 s is required for the SSTAR flight experiment. Testing was performed to evaluate the performance of two nozzle configurations on ammonia arcjet performance over this power range. One of the objectives of these tests was to quantify the effect small nozzle changes have on performance. The smaller constrictor engine (2.54 mm diameter) produced a specific impulse of about 650 s over the range of 3 to 10 kW at a specific power of 60 kJ/g exceeding the 500 600 s requirement for the SSTAR flight experiment.

Introduction

Electric Orbit Transfer Vehicles (EOTV's) propelled arcjets have the potential to provide greater launch vehicle flexibility, increase payload capability and prolong on-orbit time for commercial and military satellites. The Air Force in cooperation with TRW is now defining the STAR, Space Track and Autonomous Repositioning (formerly ELITE), a flight test designed to demonstrate critical technologies required for an operational EOTV, including the arcjet propulsion subsystem, large solar arrays and autonomous guidance, navigation and control in an integrated system. The 1800 kg spacecraft, currently scheduled for launch in 1997, will be boosted into an initial orbit at 370 km. An ammonia arcjet will then raise the spacecraft to a final altitude of 3900 km, where system degradation in the Van Allen radiation belts will be studied. The electric power for the propulsion subsystem will be provided by solar arrays with a beginning-of-life power of 10 kWe; however, solar array degradation in the Van Allen environment could result in an end-of-life power of 3 4 kWe. This mission will require a specific impulse greater than 500 600 s at an efficiency of more than 0.30 and a minimum engine lifetime of 1000 hours with the cpaability for 700 on/off cycles, (dictated by the occurrence of an eclipse once each orbit as the spacecraft enters the Earth's shadow). Each cycle will therefore consist of about 60 minutes of engine operation followed by 30 minutes with the engine off.

A candidate engine for this flight test is the 30 kWe-class arcjet that has been tested extensively at the Jet Propulsion Laboratory (JPL) [1] and is being further developed by the Rocket Research Corporation (RRC) [2]. In addition, this engine is part of the End-to End test being conducted at Air Force Philips Laboratory and at JPL [3]. This test utilizes the TRW Solar Array Simulator (SAS), the NASA Lewis Research Center (LeRC) Power Conditioning Unit (PCU) [?] and the JPL arcjet. Throttling capability of the baseline engine design [4] to power levels below 10 kWe was demonstrated in an earlier program [5] A modified design offering higher performance was developed recently at the Rocket Research Corporation (RRC) [2]. Because the arcjet performance requirements for STAR are relatively modest, the focus of the recent JPL program has been on establishing the required lifetime. A total of 1462 hours of operation with minimal electrode erosion was achieved in an endurance test of the modified design in continuous operation at 10 kWe [6]. In a subsequent test, 707 cycles (total of 701.8 hours of operation) were completed before the test was terminated by a series of external arcs [7]. The operating conditions for both

*Member of the Technical Staff, Member AIAA tests were the same. A power level of 10 kWe was chosen for both tests because it represents the most demanding condition that is likely to be encountered in the STAR mission. An ammonia mass flow rate of 0.170 g/s was used to yield a specific impulse exceeding 600 s.

The objective of the series of tests described in this paper was to demonstrate adequate performance over the entire throttling range while making minimal design changes. Small geometric changes were chosen so as to retain as much traceability of the previously demonstrated thruster lifetime information as possible. The modifications tested to date consist of two constrictor diameters and two electrode gaps.

Experimental Apparatus

The engines used in these tests are modified versions of the D-1E 30 kWe-class design [4], with different constrictor and nozzle geometries. A schematic of the thruster is shown in Fig. (1). The constrictor of the first engine was 3.81 mm (0.150 in) in diameter and had a length-to diameter ratio of unity, and the constrictor for the second engine is 2.54 mm (0.100 in) in diameter with a length-to diameter ratio of unity. Illustrations of both geometries are shown in Fig. (2). Both conical nozzles have a 19° half-angle and an expansion ratio of 40. The cathode axial position was set by first inserting the cathode into the thruster until the conical tip contacted the constrictor inlet, then retracting it by either 6.10 mm (0.240 in) or 2.03 mm (0.080 in). A 7° lapped joint seals between the pure tungsten nozzle piece and the molybdenum body piece. All other seals in the rear of the engine are accomplished by compressing grafoil gaskets. The nozzle and body are plasma spray-coated with ZrB_2, which is intended to increase the surface emittance to provide better radiative cooling.

The arcjet was mounted on a thrust stand in a stainless steel vacuum facility with an internal diameter of 1.2 m and a centerline length of 2.1 m. The arcjet exhaust was collected by a water-cooled diffuser 16 cm in diameter and pumped by a 6320 liter/s Roots blower backed by a 610 liter/s Roots blower and a 140 liter/s Stokes mechanical pump. The system is capable of achieving a vacuum of approximately 0.27 Pa with no propellant flow, and a pressure of 4.7 to 5.1 Pa for the test flow rate of 0.170 g/s. The exhaust was discharged to atmosphere through a dilution stack.

The arcjet was powered by a Linde PHC-401 arc-welding power supply, which can provide 400 A at a load voltage of 215 V continuously or 500 A at 180 V with a 50 percent duty cycle and a ballast resistance of 0.3 Ω. The power supply current ripple with this ballast resistance is approximately 31 percent peak-to peak at 10 kWe. The ballast resistance could be varied from 0.3 to 2.1 Ω. The current ripple could be reduced by increasing the ballast resistance so that a more suitable load on the arc- welding power supply could be maintained. In addition, a 1.8 Ω resistor could be added in parallel to the arcjet to increase the current load on the power supply. These modifications allowed for arcjet current levels below the operational limits of the power supply. Starting is achieved using a custom built pulse circuit described in Ref. [7].

A diagram of the propellant feed system is shown in Fig. (3). The ammonia is stored in a tank located outside the building and delivered to the thruster through stainless steel lines. The ammonia flow may be switched from the large tank to a bottle mounted on a digital scale, which allows gravimetric calibration of the mass flow rate during the endurance test. Two pressure regulators in series maintain a constant pressure upstream of a micrometer valve which is used to regulate the flow rate. The flow rate can be regulated within ±0.001 g/s of the desired value by the system and is monitored with a Sierra Instruments Side-Trak Model 830 flow meter and a Micromotion Model D6 flow meter located upstream of the metering valve. A bypass circuit allows the flow meters to be isolated to check for zero drifts during the test. The propellant gas passes through a plenum bottle on top of the tank before entering the chamber through a flange at the top. It then flows through the thrust balance and enters the engine through the cathode feedthrough at the rear.

The thruster voltage, current, thrust, propellant mass flow rate, tank pressure, plenum pressure, feed system pressures, arcjet temperature, and various facility temperatures are continuously monitored with a Macintosh computer system utilizing LabView software. The system allows unattended operation, shutting down the facility when specified engine or facility parameters exceed upper or lower bounds or when a

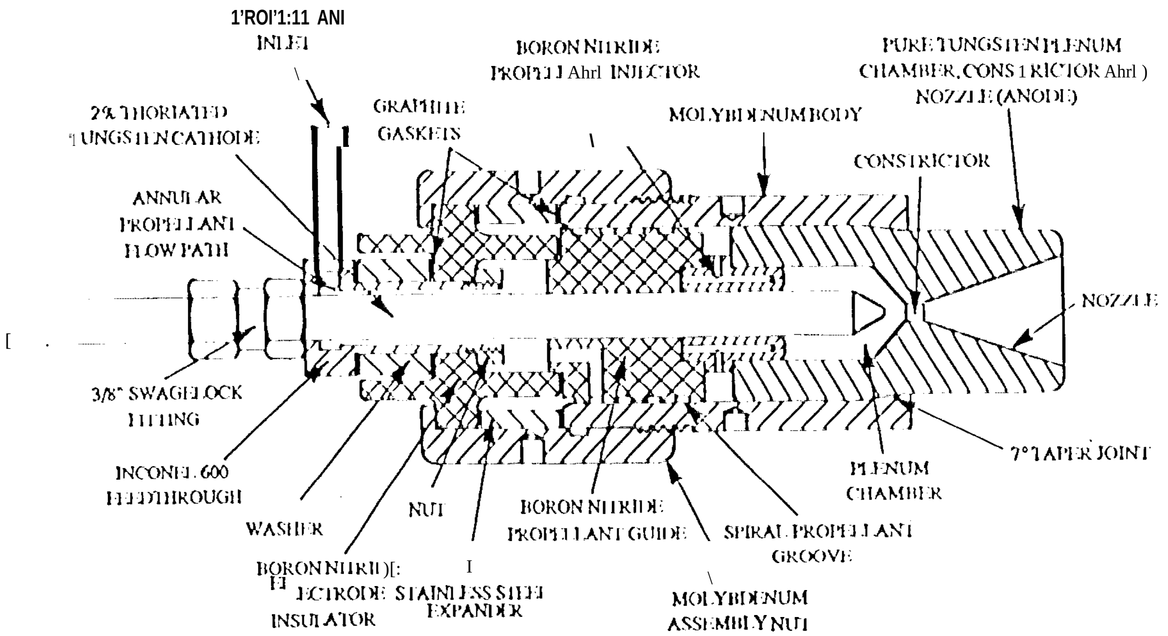

Figure 1: 30 kWe-class ammonia arcjet

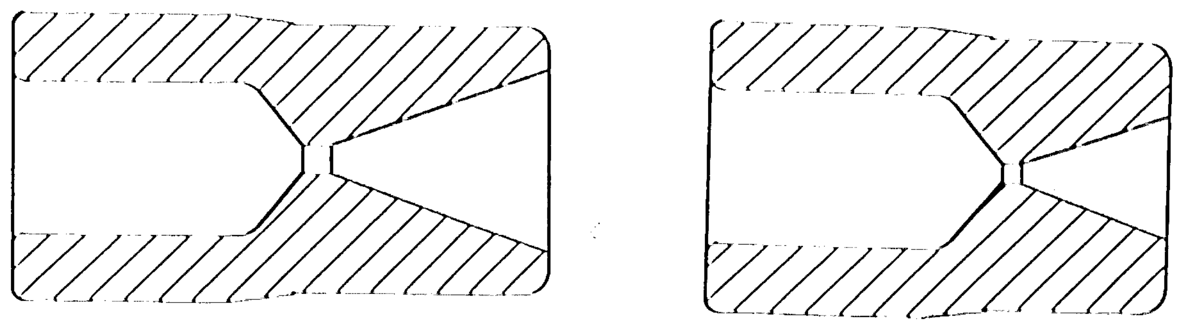

Figure 2: Nozzle geometries

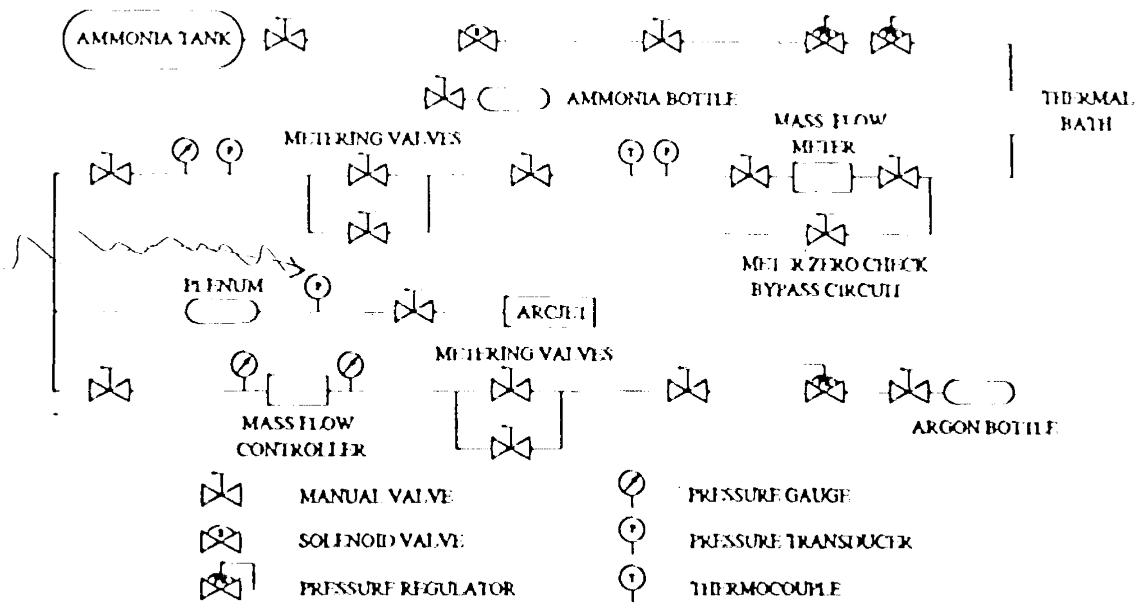

Figure 3: Arcjet propellant feed system.

computer failure occurs. The system also executes the automatic arcjet start and stop sequences, and controls the cycle timing.

The arcjet voltage is measured differentially with leads mounted near the cathode and the anode feedthroughs in a flange on the side of the vacuum tank. When corrected for the resistance between the measurement point and the engine, the measured values are accurate within ±0.2 percent. The current is determined by measuring the voltage drop across a 505.6 $\mu\Omega$ coaxial shunt with an accuracy of ±0.10 percent. A variable-capacitance type transducer mounted in a flange on the top of the tank is used to determine the tank pressure. This gauge has a range of 0–1.333 kPa and is capable of measuring the pressure to within ±0.5 percent. The pressure measured at the tank inlet is referred to as the "plenum pressure" and is approximately equal to the pressure in the arcjet discharge chamber. The thrust is determined by measuring the deflection of an inverted pendulum on which the engine is mounted with a linear variable differential transducer (LVDT). This thrust stand is based on the NASA Lewis Research Center design described in Ref. [8]. The assembly housing the LVDT and the inverted pendulum are enclosed in a water-cooled jacket to minimize thermal shifts, and an active motion damping system is used to minimize transient thrust stand motion. A set of known weights is used to calibrate the thrust stand in situ, and tests of the calibration indicate that the standard error of the measurement is approximately ±1 g. This uncertainty arises primarily because of slight hysteresis in the thrust stand motion and slight drift with time. The mass flow meters were calibrated gravimetrically, applying corrections for any zero shifts [9].

Throttling Tests of the Large Constrictor Engine Design

Two sets of tests were performed over a range of flow rates and power levels from 12 kWe to the lowest achievable power level. The first set of tests was to identify the operational range of the engine and to evaluate differences between the thrust stand designs Initial tests were performed with cantilevered beam thrust stand design (JPL design) [10]. These tests were then repeated with the new thrust balance. The resulting voltage-current characteristics are shown in Fig. (4) and the measured thrust as a function of power is shown in Fig. (5). The voltage and current measurements have standard errors that are smaller than the symbols in the plots, and the

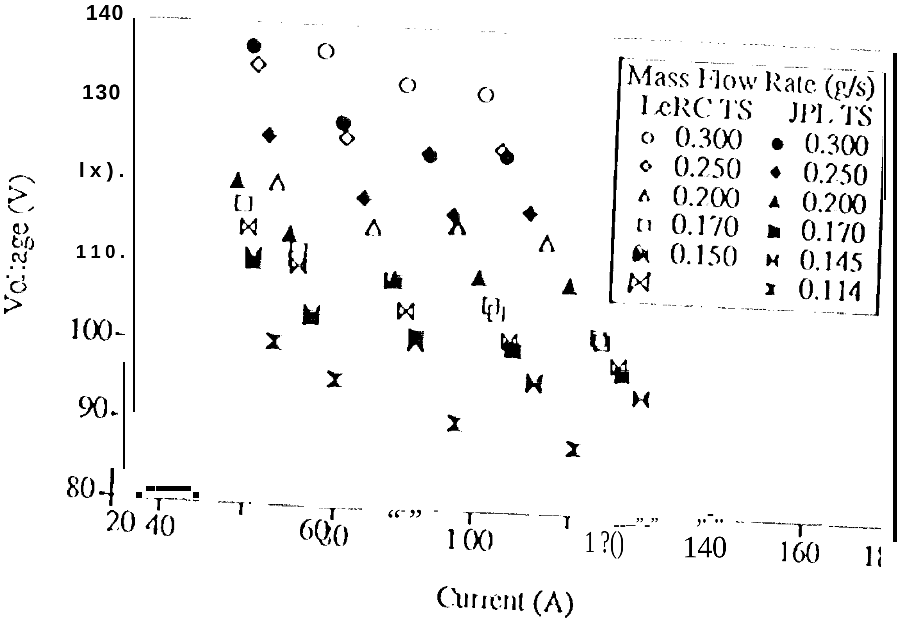

Figure 4: Voltage-current characteristics of the large constrictor engine design.

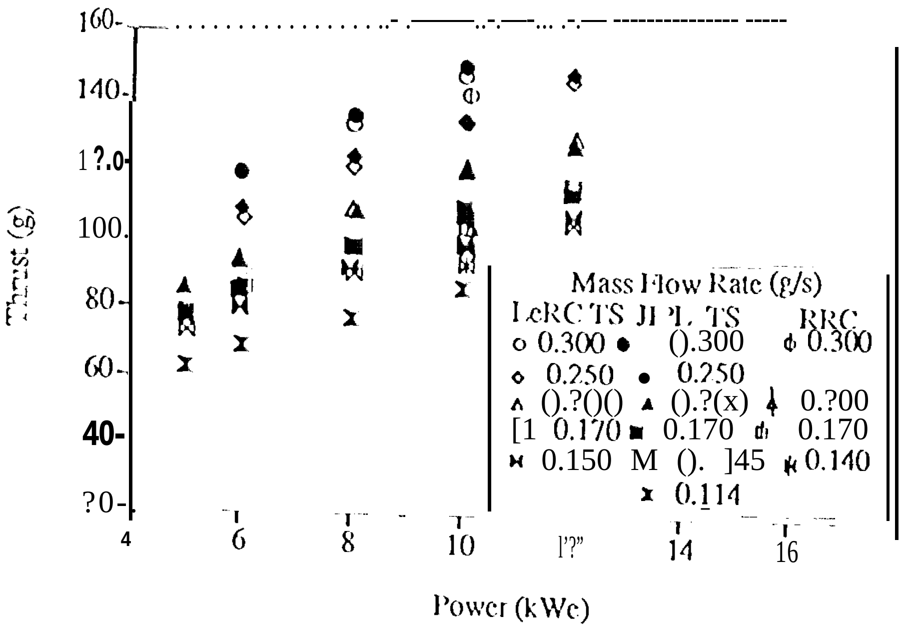

Figure 5: Large constrictor engine design thrust as a function of power.

thrust measurements performed with the new thrust stand have an uncertainty of about one gram. The thrust measured with the older thrust balance has an uncertainty of about 4 grams.

In these figures the data obtained from both thrust stands is shown for comparison. In addition, the four data points measured at 10 kWe by RRC are displayed in Fig. (5). Slight differences in the voltage-current characteristics were measured for the tests performed on the two thrust stands, although the thrust measurements agree quite well.

The cause of the differences in the voltage-current measurements has not yet been determined. It may reflect slight engine wear that occurred during the testing, an effect associated with the new thrust stand or the insulator redesign, or inherent variability in engine operation. Also, after these tests were performed, a small current (0.1 to 1 A depending on the water temperature and the contaminate concentration) was discovered in the water cooling loop for the thrust stand power tubes. The current was due to contaminates in the water. Since the concentration of the contaminates changed over time, the exact current correction for each test condition can not be specified. The thrust values from tests at Rocket Research are in general slightly lower than the values measured at JPL. To determine if these discrepancies were due to an error in the mass flow rate measured with the Sierra mass flow meter, an extensive series of calibrations were performed. The mass lost from a bottle of ammonia was monitored as a function of time at a fixed indicated flow rate to determine the true flow rate. The results of these measurements were compared with similar measurements performed during the last two years and with rotameter calibrations at a NIST traceable calibration laboratory. The results of all tests agree well, providing confidence that the measured flow rates are correct and that no shift in the calibration has occurred during the throttling tests. In addition, a Micromotion mass flow meter was added to the flow system before the throttling tests with the new thrust stand. This provides a direct comparison with the RRC flow rates, which were measured with the same model flowmeter. This instrument was also calibrated gravimetrically. The flow rates indicated by the Micromotion mass flow meter are slightly higher than those given by the Sierra meter and the gravimetric measurements. This may account for the differences noted between the JPL and Rocket Research thrust measurements. The thrust measured by Rocket Research at 0.170 g/s is slightly higher than the thrust they measured at 0.200 g/s for the same power level, which generally does not occur. The flow rate measurement uncertainty might be sufficient to explain this discrepancy.

The second series of tests was performed following the 707 cycle test [7], with the same engine to investigate the repeatability of the performance of a given geometry, and to investigate lower power levels and propellant flow rates. The variable ballast resistor and a variable shunt resistor were added to the facility to enable lower power operation. The additional resistors provided sufficient additional "load" for the Linde power supply to operate properly.

The engine performance is summarized in Figures (6) through (10). These values are based on the measurements performed with the inverted pendulum thrust stand and the Sierra mass flow measurements corrected for zero drift. The "LeRC TS" data from Fig. (4) and Fig. (5) are shown as "old data" in these figures.

Figure 6: Voltage vs current, 3.81 mm diameter constrictor, 6.10 mm gap.

The results show that the performance of a given engine can be repeated. Also, these measurements demonstrate that at specific powers greater than about 35 kJ/g this design is capable of sufficiently

Figure 7: Thrust vs power, 3.81 mm diameter constrictor, 6.10 mm gap.

Figure 9: Specific impulse vs specific power, 3.81 mm diameter constrictor, 6.10 mm gap.

Figure 8: Specific impulse vs power, 3.81 mm diameter constrictor, 6.10 mm gap.

Figure 10: Efficiency vs specific impulse, 3.81 mm diameter constrictor, 6.10 mm gap.

5/1/93

ATTD Nozzle (Throat: 0.150", L/D = 1) with 0.240" gap

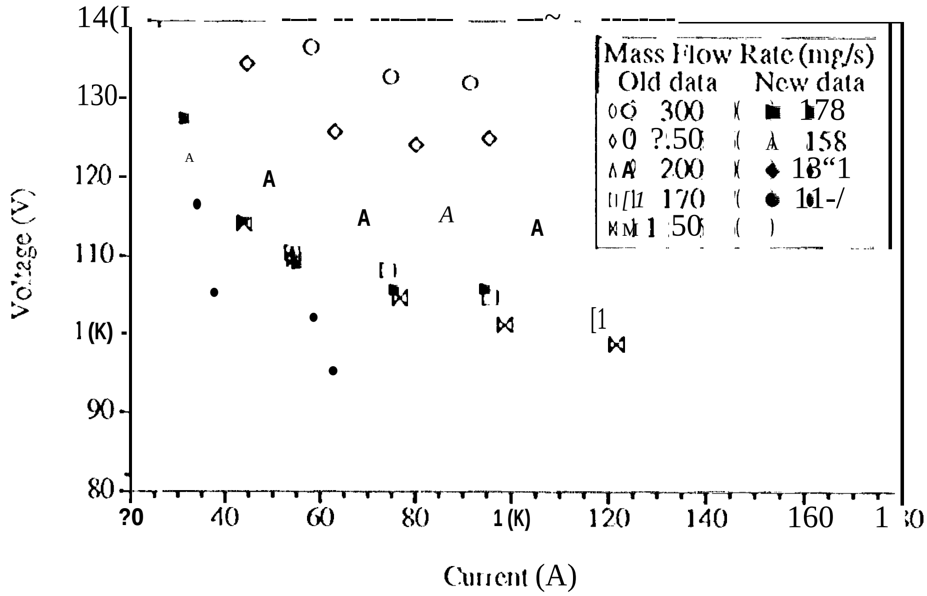

Fig. 6

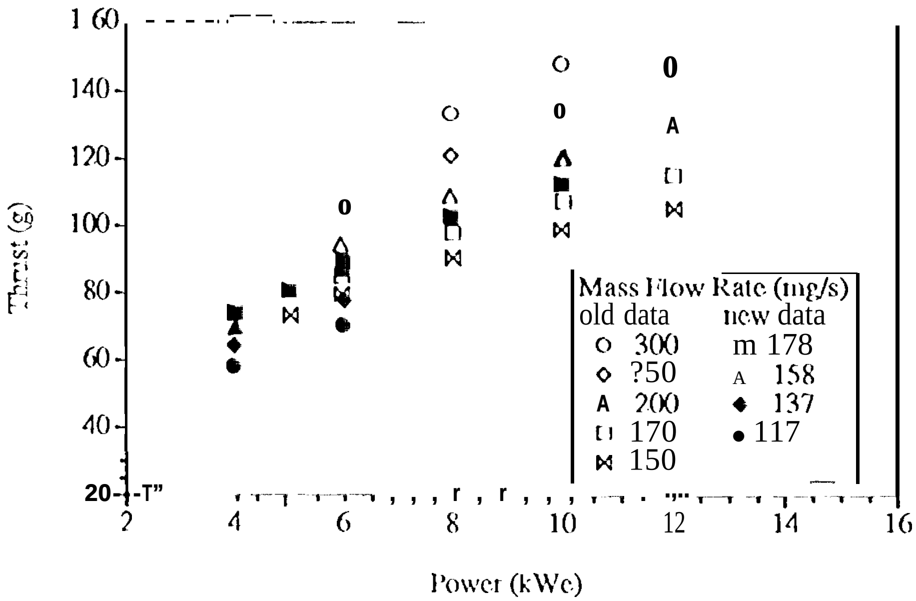

Fig. 7

ATTD Nozzle (Throat: ().1 50",1 /D = 1) with ().24()" gap

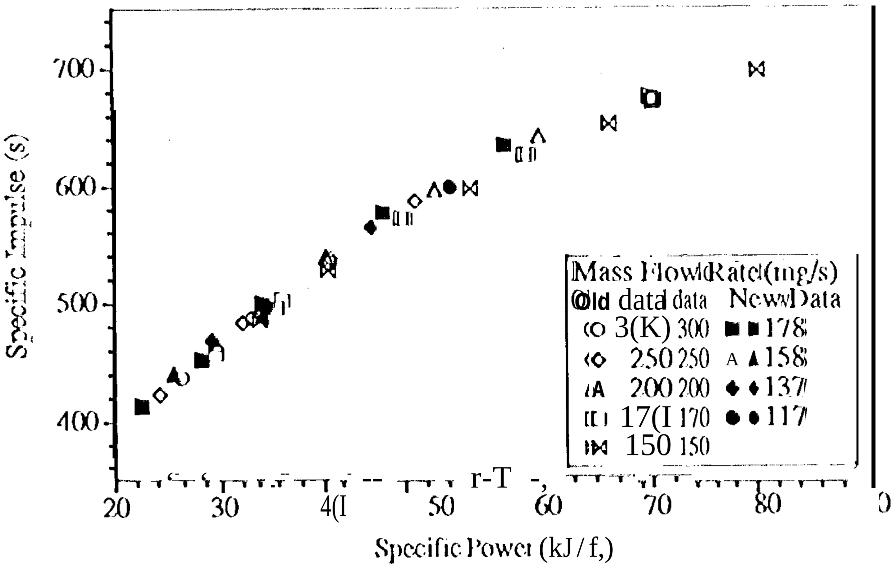

Fig 9

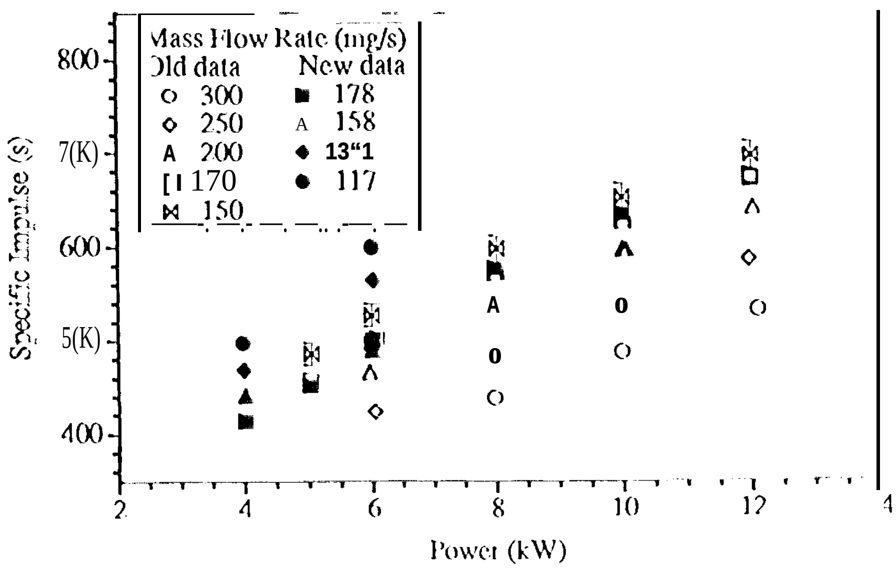

Fig 8

ATTD Nozzle (Throat: 0.150", L/D = 1) with 0.240" gap

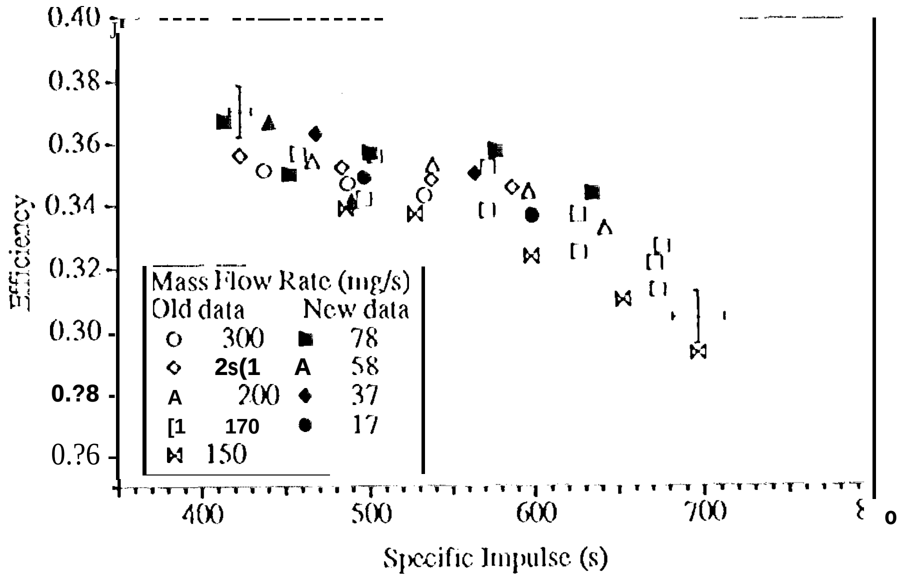

Fig 10

high performance to satisfy the STAR mission requirements. However stable operation below 4 kW was not demonstrated.

In earlier throttling tests with the 30 kW class engine it was observed that operation could be extended to lower power levels by decreasing the electrode gap [5]. To determine if the operating range of the large constrictor engine design could be similarly extended, tests were performed with an electrode gap of 2.03 mm (0.080 inches). Under these conditions operation was demonstrated to as low as 2.5 kWe. This extended range of reliable operation was accompanied by a slight performance penalty. The results of these tests are shown in Figures (11) through (15).

Figure 11: Voltage vs current, 3.81 mm diameter constrictor, 2.03 mm gap.

Preliminary Tests of an Engine with a Smaller Constrictor

To determine if small changes in the constrictor geometry can yield improvements in the engine performance at low power levels, testing of an engine with a 2.54 mm (0.100 inch) diameter constrictor has begun. A short gap (2.03 mm (0.080 in)), which generally allows easier starts, was chosen to minimize the risk of damaging the engine during initial start tests. In fact, good starts were achieved using the same start procedure as with the large constrictor engine. At 0.170 g/s and 12 kWe the ejection of

Figure 12: Thrust vs power, 3.81 mm diameter constrictor, 2.03 mm gap.

Figure 13: Specific impulse vs power, 3,81 mm diameter constrictor, 2.03 mm gap.

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6/1/93

ATTD Nozzle (Throat: (SO" DIA, 1.1/1) - 1) with 0.080" gap

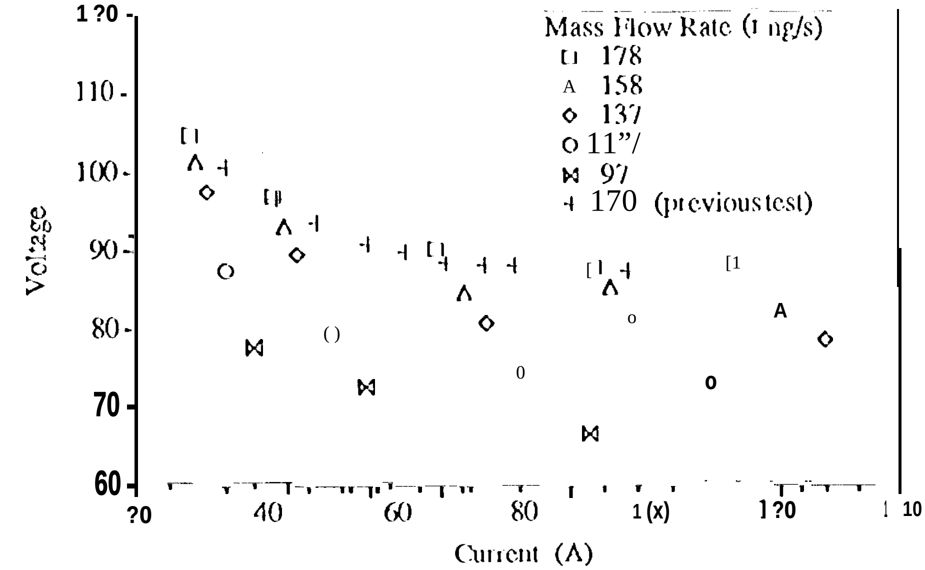

Fig 11

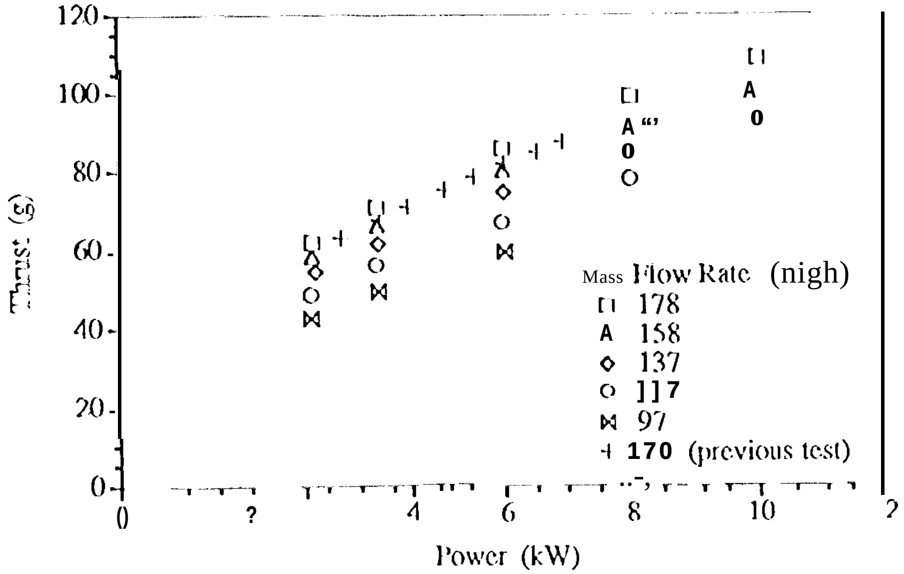

Fig 12

ATTD Nozzle (Throat: ().1 50" DIA, L/D = 1) with 0.080" gap

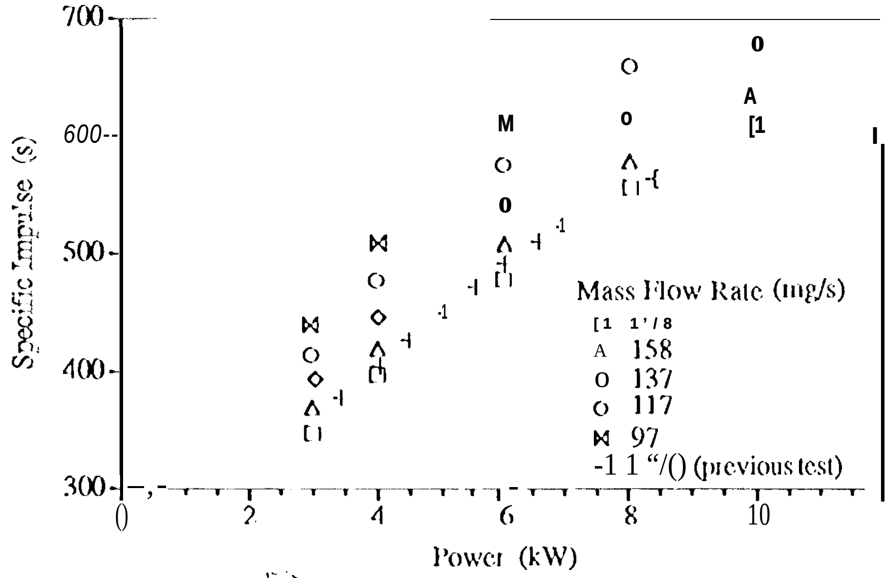

Fig 13

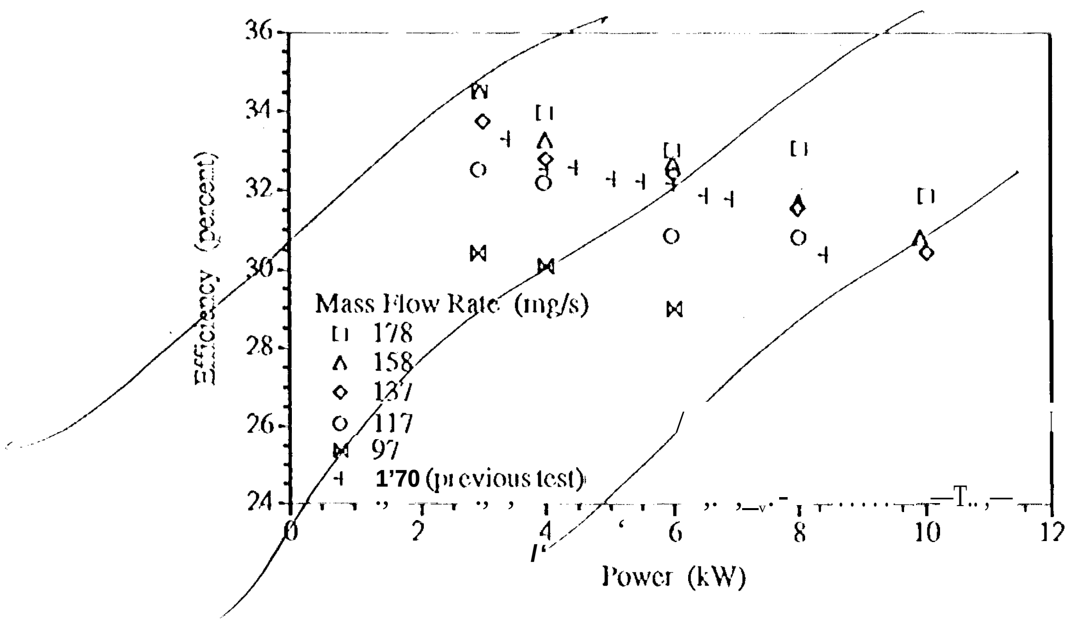

Figure 14: Specific impulse vs specific power, 3.81 mm diameter constrictor, 2.03 mm gap.

Figure 15: Efficiency vs specific impulse, 3.81 mm diameter constrictor, 2.03 mm gap.

some molten material from the nozzle was observed, so high specific powers were avoided in subsequent tests. This behavior suggests that this design may not tolerate high thermal loads as well as the nozzle with the larger constrictor. This engine was capable of operating at 2 kWe with flow rates of 44 and 54 mg/s for only about 10 to 15 minutes. This limited operating time indicates that the engine is only marginally operational at 2 kW and that the arc is probably extinguishing due to engine cooling (Tests are started at a higher power level and then the power is reduced to the low levels). The results are shown in Figures (16) through (20).

Both the specific impulse and the efficiency of the engine were improved by reducing the constrictor diameter. Further, this design is capable of a specific impulse of about 650 s over the range of 3 to 10 kW at a specific power of about 60 kJ/g (Both of the long duration tests were performed at this specific power) [6] [7]. The engine ejected some molten material during start up with a large electrode gap (6.10 mm ((1.240 in)) and operated unstably. Tests using an electrode gap of 4. 06 mm (0.160 in) are currently being performed.

Figure 16: Voltage vs current, 2.54 mm diameter constrictor, 2.03 mm gap.

Conclusions

In throttling tests of the engine developed initially for 26 kW operation was demonstrated for a range

ATTD Nozzle (Throat: 0.150" DIA, L/D= 1) with 0.080" gap

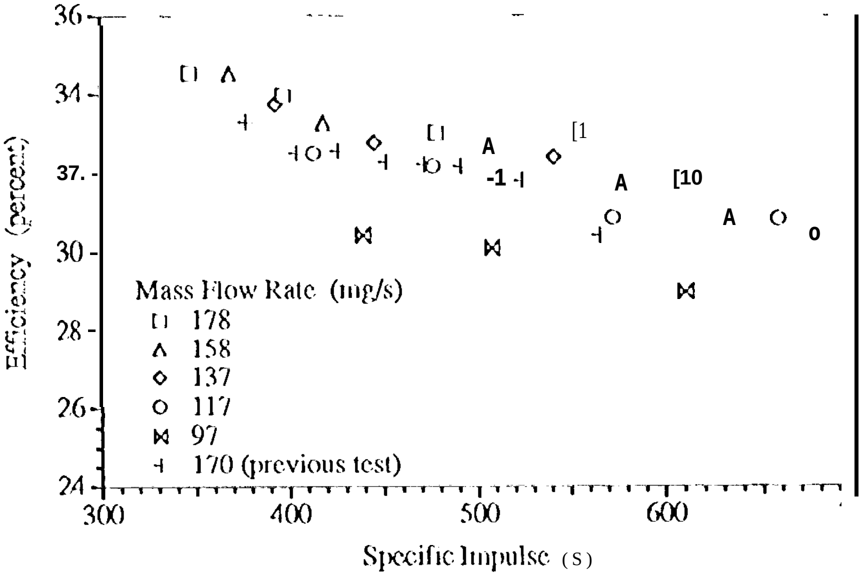

Fig 13

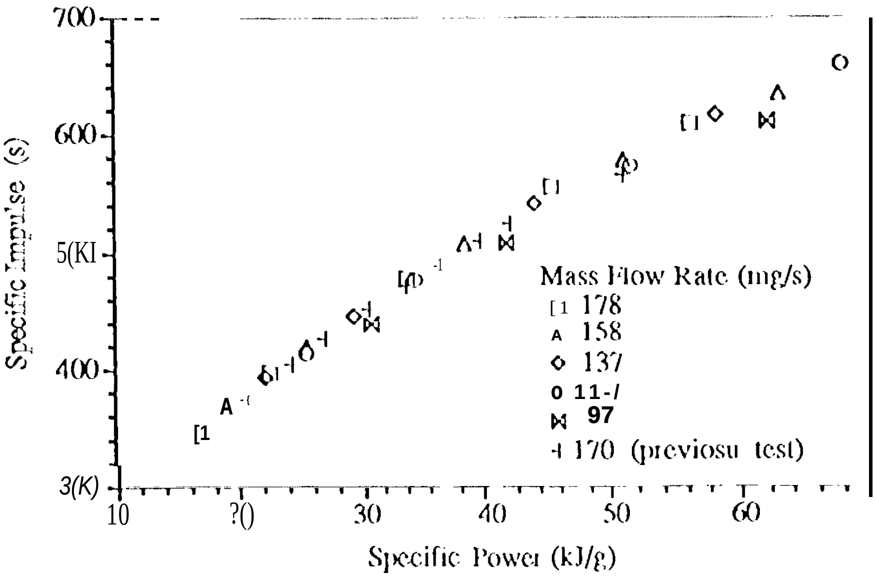

Fig 14

Figure 17: Thrust vs power, 2.54 mm diameter constrictor, 2.03 mm gap.

Figure 19: Specific impulse vs specific power, 2.54 mm diameter constrictor, 2.03 mm gap.

Figure 18: Specific impulse vs power, 2.54111111 diameter constrictor, 2.03 mm gap.

Figure 20: Efficiency vs specific impulse, 2.54 mm diameter constrictor, 2.03 mm gap.

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0.100" Constrictor, 0.080" gap

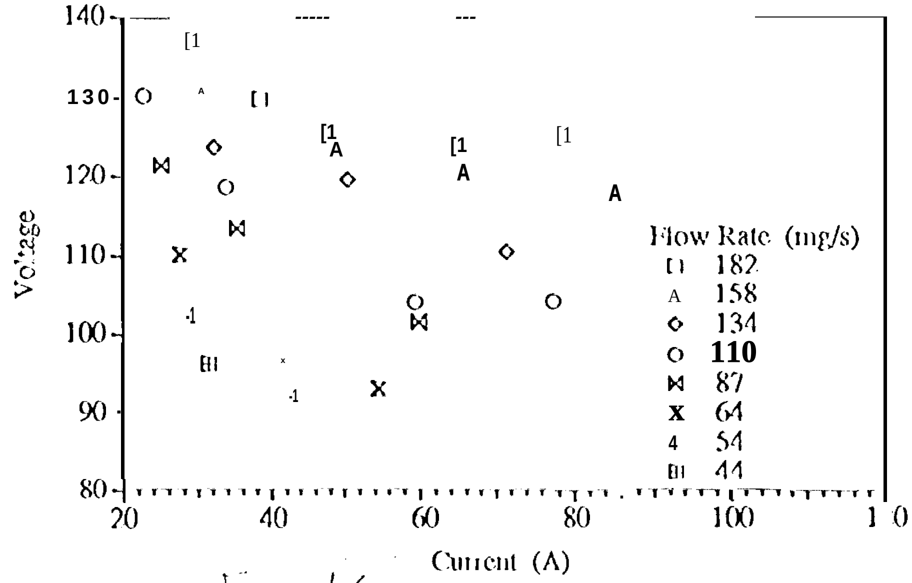

Fig 16

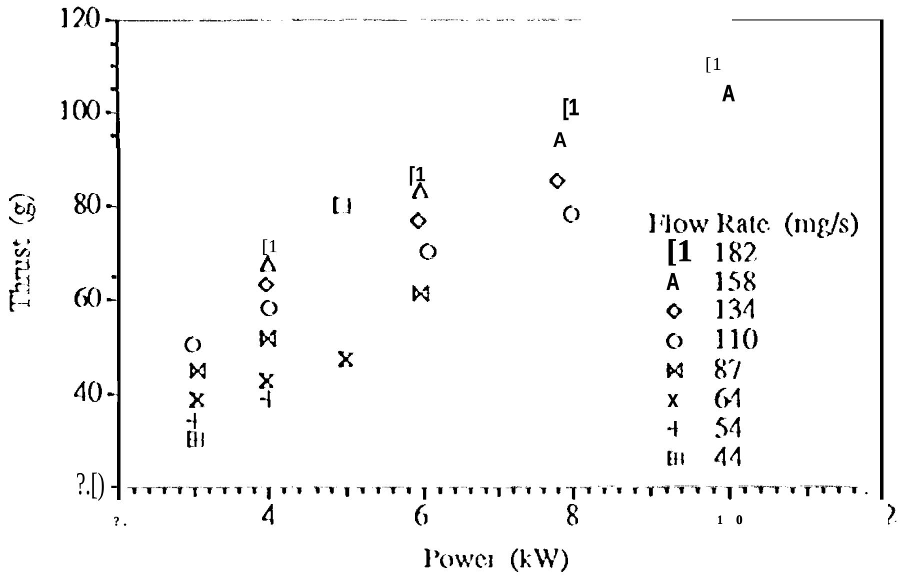

Fig 17

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0.100" Constrictor, 0.080" gap

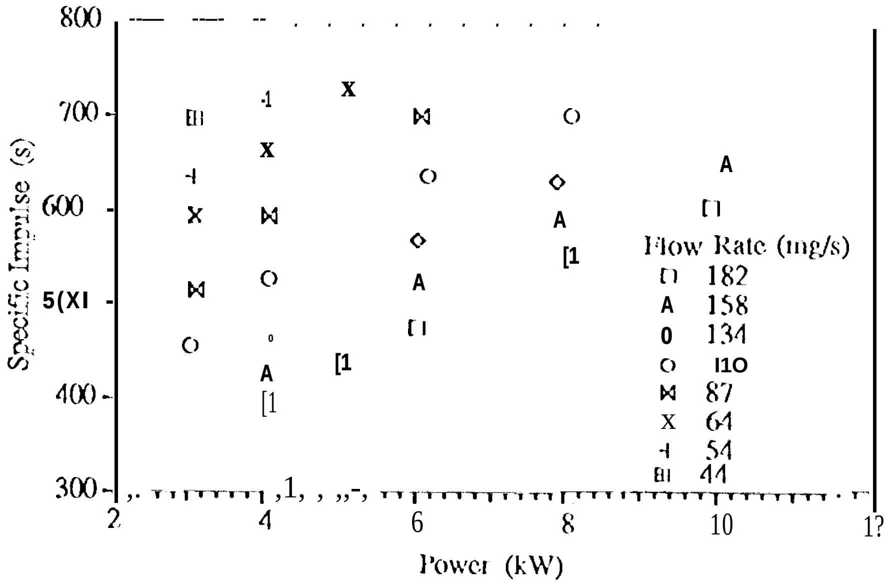
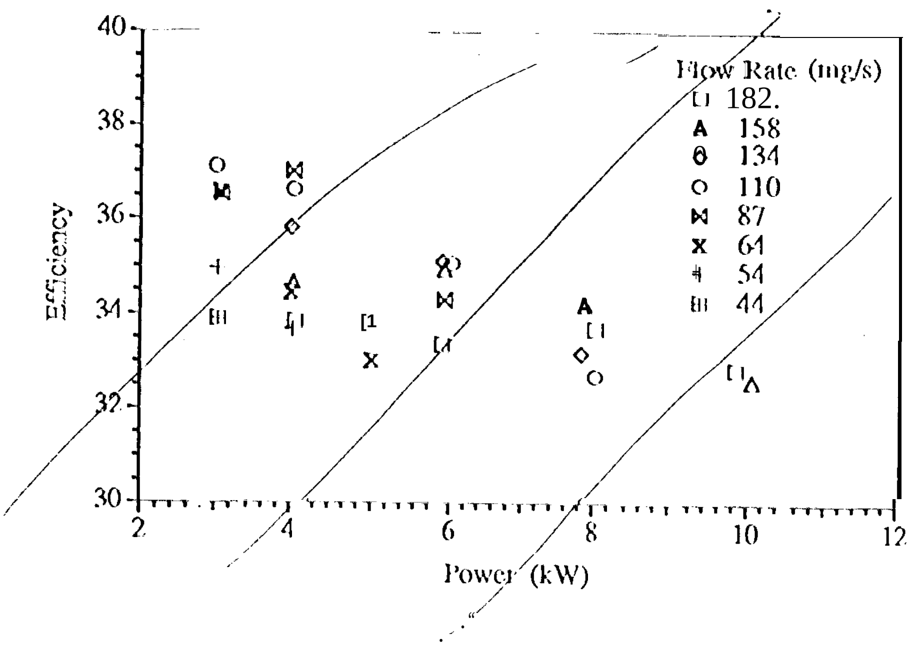


Fig 18



0.100" Constrictor, 0.080" gap

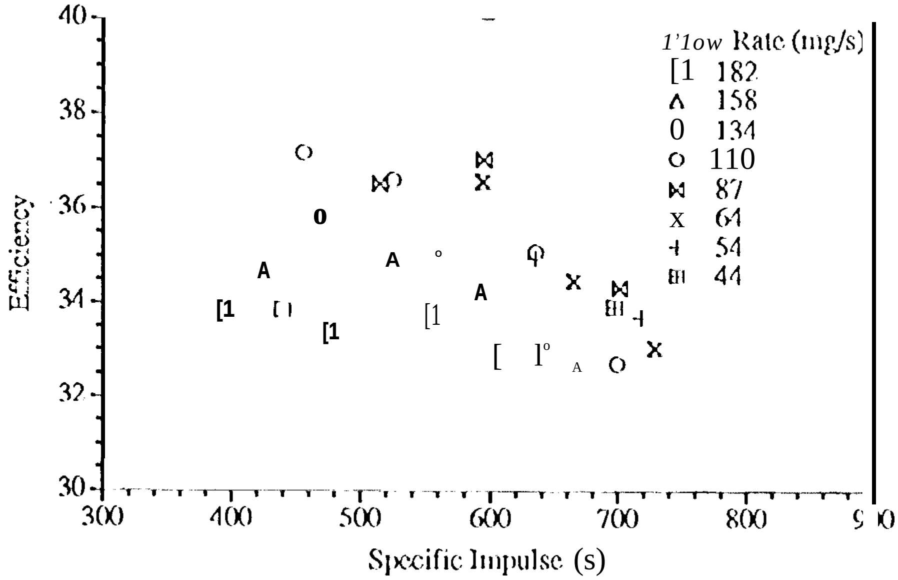


Fig 18

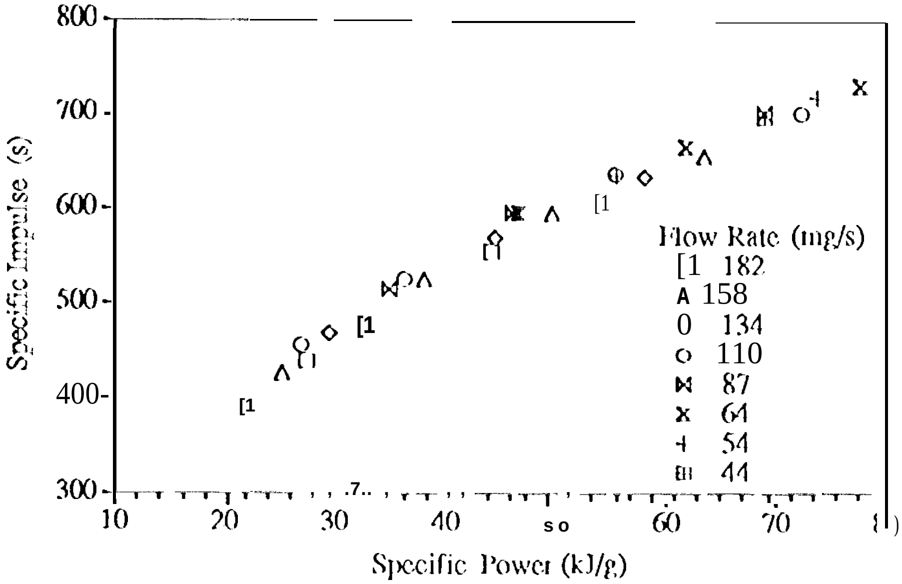


Fig 19

of mass flow rates at power levels ranging from 4 to 12 kWe. The operating range can be extended to a 3 kW power levels by decreasing the electrode gap. The engine performance for specific powers greater than about 35 kJ/g is sufficient for the SPAR mission. An engine with a constrictor diameter of 2.54 mm (0.100 inches) and an electrode gap of 2.03 mm (0.080 inches) yielded performance greater than that of the large constrictor engine. This design is capable of maintaining a specific impulse of 650 s over the entire 3 to 10 kW range. Future work will include additional performance testing, and a cyclic endurance test.

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